12-6-2020

A study on influence of Putian Port offshore wind farm construction on navigation safety

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A STUDY ON INFLUENCE OF PUTIAN PORT OFFSHORE WIND FARM CONSTRUCTION ON NAVIGATION SAFETY

By

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The People's Republic of China

A dissertation submitted to the World Maritime University in partial
Fulfillment of the requirements for the award of the degree of

MASTER OF SCIENCE

In

(MARITIME SAFETY AND ENVIRONMENTAL MANAGEMENT)

2020

Declaration

I certify that all the material in this dissertation that are not my own work have been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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Co-assessor:

Acknowledgement

In the time of the sudden outbreak of COVID-19 pandemic, with the unique experience of taking lectures on campus for the first half of the program and attending online lectures for the remaining half of it, my student life in the MSEM program jointly run by World Maritime University and Dalian Maritime University is soon coming to an end. I would like to thank the two universities for giving me the opportunity to further explore the maritime field and pursue my academic dream, and I'd also like to thank all my professors who lecture on the various subjects during the entire MSEM course.

First of all, I would like to thank my supervisor, Professor Xie Haibo. Throughout the process of writing this paper, he always gave me unremitting support and patient help with his profound professional knowledge, rigorous academic attitude, and approachable personality. A lot of efforts were put into supervising this paper. Therefore, I would like to express my deep gratitude and sincere blessings to him.

Secondly, the completion of this paper was also strongly supported by the team of Professor Liu Kezhong of Wuhan University of Technology, which provided theoretical guidance in the modeling of collision probability models. Putian Maritime Safety Administration provided a lot of technical data and suggestions to me. Fujian Sanchuan Offshore Wind Power Co., Ltd. and other institutions provided their strong support and assistance in field studies and questionnaires.

Although it is not easy to write the whole paper, my family has given me meticulous care and unlimited support in the process of completing it, so that I can finally

complete this paper without fear of various challenges. Here, I would express my sincere thanks to my family.

Abstract

Title of Dissertation: A Study on Influence of Putian Port Offshore Wind Farm Construction on Navigation Safety

Degree: MSc

The offshore wind farm is characterized by abundant and stable resources, little land occupation, little impact on the ecological environment, and it is suitable for large-scale development. It has attracted much attention in the field of clean energy in the past decades, but its impact on navigation safety in the nearby sea area cannot be ignored. This paper takes the Putian Port offshore wind farm as the research object, collects meteorological, hydrological, ship traffic flow and other data near the target water areas, and classifies and analyzes them. This paper first adopts the fuzzy comprehensive evaluation method to conduct risk assessment on navigation safety of the offshore wind farm in Putian Port, and obtains qualitative and quantitative analysis conclusions; Then, the collision probability model about the ship and the offshore wind farm was used to evaluate the navigation safety of the same offshore wind farm again, and the calculation data of the safety distance between the offshore wind farm and ship sea-route were obtained. Finally, by synthesizing the research results of the two assessment methods and summarizing the research experience, relevant suggestions for improving navigation safety of Putian Port offshore wind farm are proposed.

KEY WORDS: offshore wind farm; navigation safety; Putian Port; fuzzy comprehensive; collision probability model

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List of Abbreviations

AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
CCTV	Closed Circuit Television
cm	Centimeter
ESE	East-South-East
GIS	Geographic Information System
m/s	Meters/second
MSA	Maritime Safety Administration
MW	Megawatt
NNE	North-North-East
OWF	Offshore Wind Farm
PHA	pre-hazard analysis
SSE	South-South-East
SSW	South-South-West
UK	the United Kingdom of Great Britain and Northern Ireland
VTS	Vessel Traffic Service

Chapter 1 Introduction

1.1 Background

The grim reality of global warming has made the international community to switch to renewable energy for energy supply. Wind power, as one of the most common renewable energy sources, is favored by many. In recent years, significant technological advances in the installation, maintenance and removal of wind turbines have greatly enhanced the safety performance of wind farms and reduced the average cost associated with power generation (Zhang et al, 2018), thus further promoting the development of the wind power industry，while at the same time, the development of onshore wind power is increasingly restricted by construction land, power grid conditions and other factors. Therefore, compared with onshore wind farms, offshore wind farms have the advantages of saving land resources, having high and sustained wind speed, while having no influence by complex terrain on airflow (Peng et al, 2012).

Due to its many advantages, the offshore wind power is one of the most mature technologies, having good commercial development prospects in the current field of renewable energy and is ready to be developed on a large-scale. It has become the key policy of many countries to promote energy transition and an important way to cope with the climate change. In 2019, Europe added 3,623 MW of grid-connected wind power capacity and 502 offshore wind turbines, involving 10 wind farms. By the end of 2019, Europe's cumulative offshore wind power capacity is 22,072 MW, with 5,047 wind turbines connected to the grid, distributed in 12 countries. Among them, UK alone has a total capacity of 9,945 MW for installation (Sun, 2020).

Offshore wind power is also an important means to further promote the revolution of energy production and consumption and promote the prevention and control of air pollution in China. In 2009, China published the "Outline of Offshore Wind Farm Project Planning" (CNEA, 2009). In 2011, The National Energy Administration and the National Oceanic Administration jointly issued the "Detailed Rules for the Implementation of the Interim Measures for the Management of Offshore Wind Power Development and Construction" (CNEA et al, 2011), which made specific provisions on offshore wind power planning, contents and procedures of engineering feasibility, and construction operation management centers, and, etc. In 2015, China issued the national standard "Operation and Maintenance Regulations for Offshore Wind Farms" (CIQ et al, 2015). In 2016, the 13th Five-Year Plan for Wind Power Development issued by the National Energy Administration clearly stated that "by 2020, China's capacity for installation of offshore wind power grid will reach over 5,000 MW" (NDRC et al, 2016). According to the reply on Fujian's Offshore Wind Power Planning issued by the National Energy Administration, the capacity for installation of Fujian's offshore wind power will reach more than 2,000 MW in 2020 (CNEA, 2016).

The near-shore, large-scale and cluster effects of offshore wind farms will inevitably affect the safety of maritime traffic, safety of life at sea and protection to the marine environment. China's large-scale offshore wind power construction history is less than 10 years, and the construction technologies, norms and systems supporting navigation safety management of offshore wind power waters are not enough or even lagging behind many other countries (PTMSA et al, 2019). Although there are many planned offshore wind farms in various coastal provinces and cities, the influence of each site on navigation safety is different, and there are no strict regulations on the evaluation of the impact on navigation safety of offshore wind farms at home and abroad. How should navigation safety assessments be carried out and how should the distance between an offshore wind farm and the nearby waterway be determined before a wind farm in constructed? These are issues for study (Chen, 2017).

1.2 Purpose and significance of the study

1.2.1 Purpose

Putian Port is an important sea area for wind power planning and construction in Fujian Province, with a total planned construction capacity of 295 MW (PTDRC, 2020). This paper summarizes the effective methods of navigation safety management in water areas where offshore wind power construction is going on in China as well as other countries, then analyzes the factors of navigation environment of the Putian Port offshore wind farms, and analyzes it from both the qualitative and quantitative aspects by selecting appropriate risk evaluation methods and mathematical models. The navigation safety evaluation in offshore wind farms is carried out to provide technical guidance for the construction and navigation safety management of the Putian Port offshore wind farm.

1.2.2 Significance

At present, there are few studies on navigation safety in offshore wind farms, and most of them focus on qualitative risk assessment of navigable waters. This paper conducts a targeted study on navigation safety of offshore wind farm construction in Putian Port, which has research significance in regulating offshore wind farm construction, protecting navigation environmental resources, ensuring construction safety, and protecting legitimate interests of relevant institutions.

1.3 Development and research status of offshore wind farms

1.3.1 Research status abroad

(a) At the beginning of the 21st century, the Germanischer Lloyd formulated and applied Monte Carlo simulation method and Bayesian network method (or application software) to assess the collision risk of offshore wind farms (GWEC, 2016). At the 25th International Conference on Marine Machinery and Arctic Engineering held in Germany in 2006, D. Povel explained the usage, analysis software and development method of the Germanischer Lloyd, and provided the results of sample collision risk analysis and practical application experience of collision risk analysis (Povel et al, 2005).

(b) Marine Guidance Notes were issued by the Maritime and Coastguard Agency (MCA) for offshore wind power construction. The latest version is MGN 543(M+F)-"Safety of Navigation: Offshore Renewable Energy Installations (OREIs)-Guidance on UK Navigational Practice, Safety and Emergency Response", in which, in accordance with the concept of risk assessment and according to different risk tolerance levels, the reference standards for the distance between the offshore wind farm and the sea-route are divided, as shown Table 1 below (MCA, 2016).

Table 1: The reference standards for the distance between the offshore wind farm and the sea-route		
Distance between the offshore wind farm and the sea-route	Factors	Tolerance levels
<0.5nm (<926m)	1) X-band radar interference; 2) Ships may produce multiple echoes on shore-based radars.	Unacceptable
0.5nm~3.5nm (926~6482m)	1) Ship size and maneuverability; 2) Distance to the boundary of navigable lanes; 3) S-band radar interference; 4) Interference with ARPA or other automatic target tracking methods Impact; 5) Meet the requirements of the international maritime collision avoidance regulations.	1) If "As Low As Reasonably Practicable" (ALARP) is satisfied, it is acceptable; 2) Additional risk assessment and mitigation measures are required.
>3.5nm (>6482m)	The minimum distance between wind turbine	Widely acceptable
Source: MCA, 2016. Guidance on UK Navigational Practice, Safety and Emergency Response.		

(c) Taeyun Kim et al. in the article "Offshore Wind Farm Site Selection Study Around Jeju Island, South Korea" gave a strategy for the site selection of offshore wind farms, and carry out feasibility assessment for offshore wind farms in the coastal area of Jeju Island. The site selection criteria involve four aspects: energy resources and economy, protection of protected areas and landscapes, human activities, marine ecological environment, and site selection based on GIS and survey data (Kim et al, 2016).

1.3.2 Domestic research status

(a) Liu Kezhong published an article "Study on the Influence of Offshore Wind Farms on the Detection Performance of Marine Radars" in the Journal of Wuhan University of Technology (Transportation Science and Engineering Edition)", pointing out that the existence of offshore wind farms will interfere with marine radars to a certain extent, make land-based radars reduce their observation performance, thereby affecting navigation safety. The article uses the radar diffraction theory and radar performance parameters and analyzes the radar echo to study the impact of offshore wind farm projects on the navigation radar. The research results show that when the radar is more than 200m away from the wind turbine, the shadow area formed under the interference of the wind turbine has little influence on the observation, but the radar observation and tracking of the objects inside and around the wind farm are more difficult. The safety of navigation poses a certain threat (Liu et al, 2010).

(b) Li Daoke in the article "Fujian Offshore Wind Farm Site Shipping Safety Risk Analysis" in "China Navigation", based on the traffic characteristics of the planned water area of the offshore wind farm in Fujian, identified the main shipping risks in the sea area near the offshore wind farm, and used the combined method of expert investigation and pre-hazard analysis (PHA) to conduct quantitative and qualitative analysis of shipping risk factors, and obtained a ranking of the impact of 18 offshore wind farms on shipping safety from high to low, and make a reference for the development sequence of offshore wind farms (Li, 2015).

(c) Chen Xiaolong adopted a combination of analytic hierarchy process and entropy value method to determine the weight of the optimization index in his master's thesis of Dalian Maritime University "Research on the Optimization of Offshore Wind Farm Sites Considering Navigation Safety Factors", and further used the gray correlation analysis method to obtain the correlation coefficient between the index value of each site and the ideal value. Then, the gray comprehensive optimization model is used to sort and optimize the planned site. Finally, four planned wind farm sites in the Tangshan sea area are used as examples for the application (Chen, 2017).

(d) Zhang Huawei applied the analytic hierarchy process and multi-level fuzzy comprehensive evaluation method to analyze the navigation safety of Tangshan Port offshore wind farm in his master's thesis of Dalian Maritime University "Tangshan Port Offshore Wind Farm Navigation Safety Risk Assessment and Maritime Supervision Research", and a comprehensive evaluation of the risks was carried out, then the navigation safety of offshore wind farm was analyzed based on the evaluation results. Finally, the thesis combined with the current maritime supervision status, and proposed the three-stage navigation safety maritime supervision recommendations for offshore wind farms (Zhang, 2017).

(e) Zhou Peng analyzed the navigation risks of offshore wind farm area using AIS data in Xiapu within a year, and used Floyd algorithm programming to optimize the conflict route of Xiapu offshore wind farm area based on the shortest distance, so as to propose a preliminary solution to the recommended route conflict (Zhou, 2020).

1.4 Main contents of the study

The research content of this paper mainly includes the following aspects:

(a) The current status of research on the impact of offshore wind farms on navigation safety at home and abroad.

(b) The navigational and environmental data around the Putian Port offshore wind farm, including the construction plan of the offshore wind farm, natural conditions, navigational conditions, and ship traffic flow.

(c) The identification and classification of navigation risks on Putian Port offshore wind farm, and the establishment of an evaluation system.

(d) The analysis of navigation safety on Putian Port offshore wind farm based on the fuzzy comprehensive method.

(e) The analysis of navigation safety on Putian Port offshore wind farm based on the collision probability model.

(f) The synthetic usage of research results of each analysis method, and the suggestions of navigation safety management on Putian Port offshore wind farm.

1.5 Research methods and the technical route

1.5.1 Research methods

(a) Literature analysis: To accumulate knowledge on offshore wind farms, navigation safety, risk evaluation, etc. through reading a lot of literature on the topic, which laid a solid foundation for the research of this paper.

(b) Field study and expert consultation: First, for offshore wind power projects, I went to the local maritime authority to collect the meteorological, traffic flow and other data of the nearby sea area to understand the current status and future planning of nearby ports, anchorages, and waterways. Then I visited the owners and builders of some offshore wind power projects to obtain the engineering feasibility study report and construction plan of the project for understanding the safety measures during construction and operation of the project.

(c) Theoretical research: Literature review, normative reference, data analysis, expert consultation and other methods are used to rationally select index weights for the research on the impact assessment of offshore wind farms on navigational environment, and specific research is conducted through fuzzy comprehensive evaluation method and collision probability model.

1.5.2 Technical route

The technical route of this paper is shown in Figure 1.

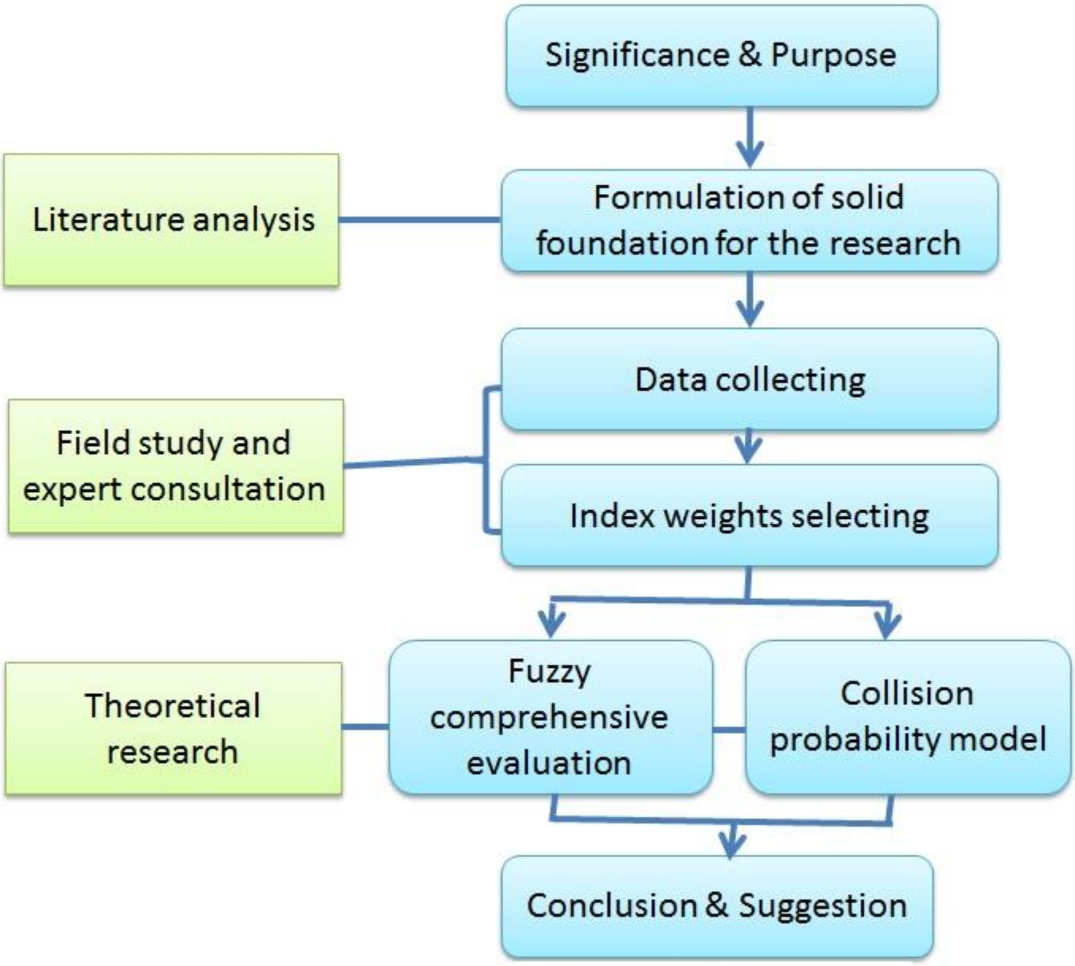

Figure 1： Technical route of this paper

Source： Author

Chapter 2 Analysis of the navigational environment information of Putian Port offshore wind farm

2.1 Status of Putian Port offshore wind farm

Putian is located in the middle of the coast of Fujian, with a coastline of 443 kilometers and a sea area of 11,000 square kilometers. There are three major bays in the jurisdiction: Xinghua Bay, Meizhou Bay and Pinghai Bay. There are Jiangyin Port and Xinghua Port in Xinghua Bay, and Meizhou Bay Port has four port areas, Douwei Port, Dongwu Port, Xiuyu Port and Xiaocuo Port. The currently planned offshore wind farms in Putian City include Shicheng offshore wind farm, Nanri offshore wind farm, Damaiyu offshore wind farm and Pinghaiwan offshore wind farm (FJWHI, 2017).

The Shicheng offshore wind farm project is located in the sea area of Xinghua Bay, with Pinghai Peninsula in the south, Huanggua Island in the west and Niuyu Island in the east.

The Nanri offshore wind farm project is located on the south side of Xinghua Waterway and on the northeast side of Nanri Island. It is 1 to 14 kilometers away from Nanri Island and includes areas A, B and C.

The Damaiyu offshore wind farm is located on the east side of Nanri Island, reaching to Damaiyu in the east and Yangyu in the south, with a length of 7.5 kilometers from north to south and a width of about 5 kilometers from east to west.

The Pinghaiwan Offshore Wind Farm is located in Pinghai Bay in the southeast of Xiuyu District, Putian City, with Daitou Peninsula in the west, Nanri Island in the north, and Meizhou Island in the southwest. The total area is about 245 square kilometers, and the planned total scale is 1,200 MW. The site is divided into six areas: A, B, C, D, E, F area.

The distribution of offshore wind farms and main waterways in Putian City are shown in Figure 2.

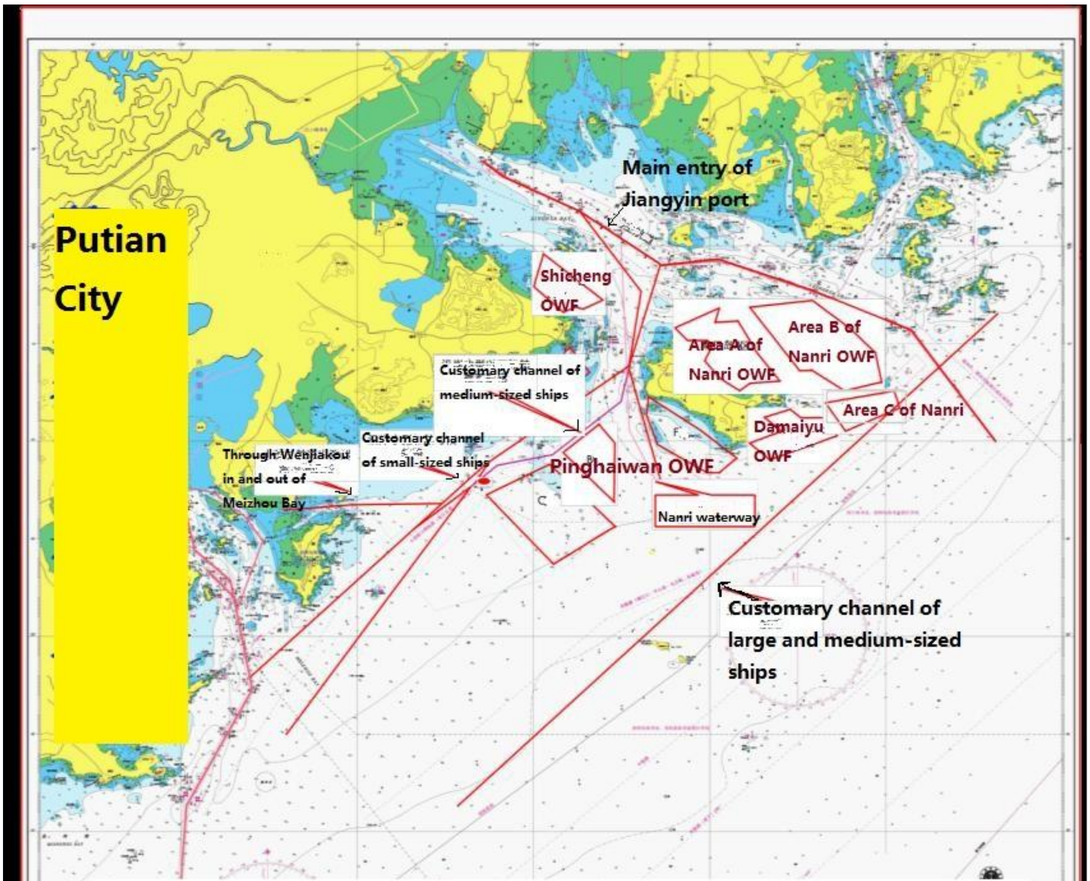

Figure 2 ：The distribution of offshore wind farms and main waterways in Putian city

Source： FJWHI, 2017. Fujian Province Offshore Wind Farm Project Planning Report

2.2 Navigation environment near Putian Port offshore wind farm

2.2.1 Natural conditions

(a) Meteorological conditions

Putian City has a southern subtropical oceanic climate with obvious seasonal climate. From October to February, March to May, June to October of each year, it is often hit by cold waves & heavy winds, fog and typhoons alternately. The port area is located at the north mouth of the Taiwan Strait, and is affected by the narrow tube effect. The average annual gale is greater than Beaufort scale 6 for 162.9 days (PTMB, 2019). The offshore wind farms in Putian City are concentrated in the Xinghua Bay, or the Pinghai Bay which is close to the Xinghua Bay. The nearest weather station is Pingtan Weather Station. According to the weather data of Pingtan Weather Station from 1958 to 2019, the meteorological conditions in the area around the offshore wind farms in Putian Port have the following characteristics:

The wind direction in the whole year is north-northeast with a frequency of 47%; the second is northeast with a frequency of 16%; the third is south with a frequency of 12%; east to southeast and west to northwest are rarely seen. The annual average wind speed is 8.6m/s. The maximum annual average wind speed is 9.6m/s. The average annual foggy day is 21 days (PTWS, 2019). The maximum number of foggy days in a year is 35 days. A total of 153 tropical cyclones landed on the coast of Fujian, with an average of 2.6 per year, with 5 in the highest number of years. (FJMMO, 2019).

(b) Hydrological conditions

The tidal pattern in the Putian sea area is a regular semi-daily tide type, with an average annual high tide level of 286 cm and an average annual low tide level of -228 cm. The maximum tidal range is 739 cm, and the minimum tidal range is 497 cm. According to the hydrological observations conducted by the Third Institute of Oceanography of the National Oceanic Administration in this sea area, the maximum average velocity of the ebb tide in the Putian sea area is 0.6 m/s and the flow direction is 162°, and the average velocity of the rising tide is 0.66 m/s at maximum and the flow direction is 325°(Third IO, 2016).

According to the data from the First Institute of Oceanography of the National Oceanic Administration in September 2014, the sea wave near the Putian Port offshore wind farm had a frequency of 77% in the direction of ESE, and a frequency of 10% in the direction of SSW. The strong wave was SSE, the maximum wave height was 8.3 meters, and the second strong wave was in the NNE direction, and the maximum wave height was 7.5 meters. The average wave height in all directions was 1.0~4.0 meters (First IO, 2014).

2.2.2 Navigation conditions

(a) Current status of the Port

There are Jiangyin Port and Xinghua Port near Putian Port Offshore Wind Farm. Among them, Xinghua Port currently has Sanjiangkou Operation Area, Hanjiang Operation Area, Shicheng Operation Area, Beigao Operation Area, and Nanri Operation Point. There are currently 9 productive berths, all of which are 3,000-ton berths or below, with an annual cargo throughput of 1.26 million tons; one 3,000-ton berth is under construction. Jiangyin Port is composed of four operation areas, Bitou, Niutouwei, Wan'an and Xialong. The carriage of containers, coal, bulk cargo and chemical products is the main type of cargo transportation, and it also takes into account the ro-ro transportation of commercial vehicles. There are currently 10 berths in Jiangyin Port, including 7 deep-water berths, with a designed throughput capacity of 7.5 million tons and containers of 1.75 million TEU (Port Authority of Meizhou Bay, 2020).

(b) Current status of the channel

The main waterways of Putian Port include the main entry channel of Jiangyin Port, the planned channel of Xinghua Bay, the Nanri Waterway, the channel of through WenJiakou in and out of Meizhou Bay, the customary channel for small and medium-sized ships, the channel of large and medium-sized ships in and out of Meizhou Bay, and large ships near-shore route, Meizhou Bay main channel, outer channel (Port Authority of Meizhou Bay, 2020).

2.3 Analysis of vessel traffic near Putian Port offshore wind farm

Through the use of the AIS data platform of Wuhan University of Technology, the data of vessel traffic of Putian Port from January to December 2017 were collected. And through the use of AIS automatic plotting system and risk analysis software to process the data, to classify and sort out the data by the temporal and spatial relationship, to refine the main traffic flow parameters, to perform cluster analysis on the track data; and to count the number and location distribution of ships on each channel, the ship size distribution, the width of the traffic flow and the distance between the traffic flow and the wind farm. Finally, the time and space characteristics of the traffic flow in the Putian sea area and the impact between traffic flow and offshore wind farms are analyzed.

(a) Statistics of traffic flow

The ship traffic volume of a certain section is selected as a statistical indicator, and the scale of the ship traffic flow in the corresponding section area is obtained by analyzing the number of ships passing through the section. According to the location of the main routes in Putian Port, the distribution characteristics of the ship’s track obtained by observation, and the planning and construction conditions of the offshore wind farm, the following 7 sections are selected: the main entry channel section of Jiangyin Port, the Xinghua Bay planning channel section, the channel section of through WenJiakou in and out of Meizhou Bay, the customary channel section of small and medium-sized ships (west of Nanri Island), the customary channel section of small and medium-sized ships (Pinghai Bay), the customary channel section of coastal large and medium-sized ships, and the outer channel section. The average traffic volume of each section is shown in Table 2.

Table 2: Average daily traffic volume (unit: Times) of each channel section of Putian Port			
Channel section	Average Daily Traffic Volume	Average Daily Traffic Volume (Northbound)	Average Daily Traffic Volume (Southbound)
Main entry channel section of Jiangyin Port	42	21	21
Xinghua Bay planning channel section	18	8	10
The channel section of through WenJiakou in and out of Meizhou Bay	18	10	8
Customary channel section of small and medium-sized ships (west of Nanri Island)	97	39	58
Customary channel section of small and medium-sized ships (Pinghai Bay)	113	44	69
Customary channel section of coastal large and medium-sized ships	135	72	63
Outer channel section	80	42	38
Source：Author			

(b) Statistics on ship length

Ship length is one of the main characteristic parameters of ship traffic flow, and it is also an important factor in the study of ship navigation risks in offshore wind farms. Generally speaking, the longer the ship length and the larger the tonnage, the more serious the consequences of the collision between the ship and the wind farm. Through statistics on the length distribution of ships on various routes, the distribution of ship scales on each channel can be obtained. The statistics of ship length on each channel along the coast of Putian in 2017 are shown in Figure 3.

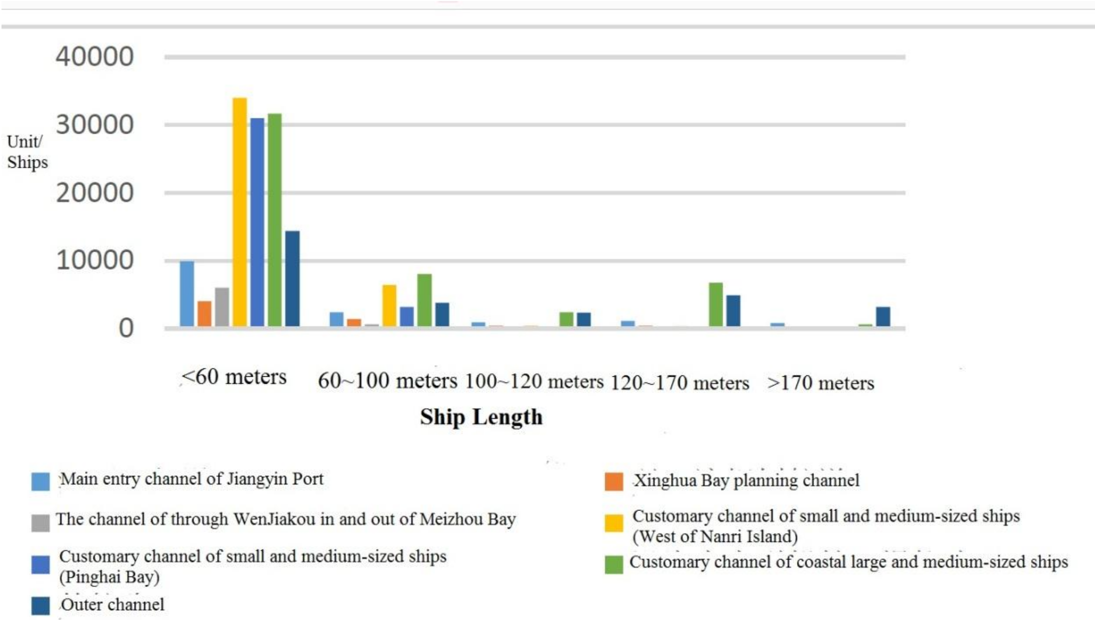

Figure 3: The statistics of ship length on each channel along the coast of Putian in 2017
Source: Author

(c) Statistics of the distance between the channel and the offshore wind farm

The distance between the channel and the offshore wind farm is a main parameter for studying the interaction between ship traffic flow and wind farms, and it is also an important indicator for further exploring the collision risk between ships and wind farms. It has important practical significance for setting up a scientific location of wind farm. The distance between the ship channel and the planned offshore wind farm in Putian Port is shown in Table 3.

Table 3: The distance (unit: Meters) between the ship channel and the planned offshore wind farm in Putian Port							
		Main entry channel of Jiangyin Port	Xinghua Bay planning channel	The channel of through WenJiakou in and out of Meizhou Bay	Customary channel of small and medium-sized ships	Customary channel of coastal large and medium-sized ships	Outer channel
Shicheng offshore wind farm		5819	1700	17619	4603	27081	33548
Nanri offshore wind farm		1502	4647	15544	1225	2776	8671
Damaiyu offshore wind farm		11367	10546	10666	11936	4232	9664
Pinghaiwan offshore wind farm	A	12303	2986	7455	1798	20238	30477
	B	16001	cross	cross	1869	9759	19372
	C	21353	0	cross	0	8051	17862
	D	32518	13949	8149	6529	3340	15269
	E	27421	9671	0	0	8195	20348
	F	11872	2115	4015	5256	7911	15718
Source： Author							

Chapter 3 General analysis of navigation safety risks of Putian Port offshore wind farm

3.1 Navigation safety risk characteristics of Putian Port offshore wind farm

Everything has its own characteristics and development patterns. It is of great significance to strengthen navigation safety management of offshore wind farms by fully understanding the characteristics of navigation safety risks. According to the theoretical research of Wang Wenkai (Wang, 2013), Zhang Huawei (Zhang, 2017) and other scholars, as well as the analysis of the navigation environment information of the Putian Port offshore wind farm in Chapter 2 of this paper, the navigation safety risks of the Putian Port offshore wind farm have the following characteristics.

(a) Natural environmental risks

The operating life of offshore wind farms is generally 30 years. Compared with construction, the operating time is longer, and the current domestic management experience needs to be improved, and the builder has a weak ability to deal with risks. Therefore, there are certain unpredictable risks during the operation of the project. The natural environment of the project construction sea area, such as wind, waves, fog, etc., will affect the project and may pollute the sea area environment.

(b) Port environmental risks

The construction of offshore wind farms will have a certain impact on the port environment, such as affecting the construction of port anchorages, affecting the future construction of the port area, leading to changes in maritime communications and nearby magnetic fields. The location of offshore wind farms should meet the requirements of relevant zoning and planning as much as possible, and coordinate the relationship with military affairs, maritime affairs, fisheries and environmental and ecological protection, and have good hydrogeology, grid connection, transportation and construction conditions.

(c) Traffic environmental risks

The offshore wind farm is close to the recommended sea-route, and it is bound to have a certain mutual influence with the current marine traffic in the water areas, which will affect the activities of other nearby offshore and underwater activities. During the construction of the offshore wind farm, passing ships have an impact on the normal construction of the project, such as: collisions between passing ships and construction ships, and passing ships touching the foundation of the wind turbine. During the operation of the offshore wind farm, there is a risk that passing ships sail along the original customary route or to save navigation costs and time. There is a chance that they may touch the wind turbines when they cross the wind farm area.

(d) Risks of illegally transport activity

Driven by profits, a large number of inland vessels are illegally engaged in sand mining and maritime transport activities in Xinghua Bay. These ships are in poor condition and with unqualified crews, evading supervision. The frequent activities of these ships have bad influence and interference with the navigation and operation of offshore wind farm construction ships, and may even cause accidents.

(e) Risks of the construction and operating conditions

The construction and operation of offshore wind farm directly affect navigation safety. If the construction unit and operation unit are backward in construction equipment and technology, the construction ship or maintenance ship is in bad condition, the technical quality of the operators is poor. The navigation environment will be affected.

(f) Risks of management of offshore wind farm owners

Due to the pursuit for profit, insufficient investment in navigation safety; lack of awareness of offshore construction safety; insufficient awareness of the impact on the navigation safety; knowledge of offshore wind farm construction operation areas, safe operation areas or prohibited navigation areas are limited, thinking that it is absolutely safe once it is set up safe area; the owner is not clear about its main responsibility and the safety responsibility system is not in place. All this puts offshore wind farms at risk.

3.2 Risk assessment factors for navigation safety of Putian Port offshore wind farm

According to the navigation safety risk characteristics of the Putian Port offshore wind farm, combined with the theoretical research of different scholars such as Wang Wenkai and Zhang Huawei, and through field study on the relevant owners and construction units of the Putian Port offshore wind farm, it is concluded that there are more than 20 risk factors which impact on the navigation safety in Putian Port offshore wind farms in five categories. However, due to the use of the fuzzy comprehensive method and collision probability model, this paper only focuses on the following five evaluation factors.

(a) Wind

During the construction period, the transport ship will be affected by the wind which may lead to the drifting motion of the ship, and there will be a certain risk of collision between nearby sailing ships, anchored ships and nearby obstructions; the safety of construction ships and guard ships will be affected by wind, including excessive wind that increases the difficulty of construction operations, wind intensifies ship deflection, drift and rolling motion, increasing the difficulty of steel pipe pile lifting, jacket lifting, fan lifting, submarine cable laying, etc., and also affecting positioning and lifting operations accuracy.

During the operation process, the wind turbines and warning ships will be affected by the wind. The jackets and wind turbines are relatively tall and have a large wind area. When affected by strong lateral winds, they may drift or even tilt, and the wind turbines would stop running for its own protection. Maintain and guard ships will have difficulties in operation, anchoring and navigation.

(b) Ocean current

The impact of ocean currents on ship navigation is mainly manifested in that the ship is affected by the ocean currents to produce a certain drifting motion, which increases the difficulty of ship maneuvering, and increases the risk of collision between engineering transport ships, construction ships and passing ships. Excessive flow velocity affects the positioning and positioning accuracy of the construction ship, and the installation accuracy of facilities such as pile foundations and fans, which easily makes the submarine cable deviate from the predetermined routing line, increasing the difficulty of the submarine cable laying operation.

(c) Wave

Waves may cause the ship to roll in a certain way. Rolling with large inclination angles not only directly endangers the safety of the ship, but also induces a large number of waves on deck. During the construction period, the waves may make construction ships and transport ships shake continuously, increase the swing range of the ship, and reduce the stability of the ship. At the same time, it increases the difficulty of loading and unloading, hoisting, docking and submarine cable laying, and affects the construction accuracy.

(d) Recommended route

As described in 2.3 of this paper, there are 7 main routes near the Putian Port offshore wind farm. Among them, the channel of through WenJiakou in and out of Meizhou Bay will pass through Zone B and Zone C of the Pinghaiwan offshore wind farm, and the recommended route for ships will be severely affected. Ships sailing in accordance with the recommended route are at risk of collision with the construction ships, maintenance ships, guard ships and wind turbines of the wind farm. The boundaries of Zone C and Zone E of Pinghaiwan offshore wind farm almost overlap with the customary route of small and medium-sized ships. When the ship passes through this water area, if it loses control or drifts under the influence of wind, current and other factors, it may cause collision accidents between ships and wind turbines.

(e) Ship traffic flow

As described in 2.3 of this paper, the traffic density and ship length of the seven main routes near the Putian Port offshore wind farm are all different. According to the location of the traffic flow and the wind farm, the traffic flow of these ships will be blocked by the wind farm. The customary navigation methods of ships will be severely affected, and the construction ships, maintenance ships, guard ships and wind turbines of wind farms are at risk of being touched.

Chapter 4 Analysis of navigation safety of Putian Port offshore wind farm based on fuzzy comprehensive method

The navigation safety risk assessment of offshore wind farms is the qualitative and quantitative analysis, evaluation and prediction of the navigation safety or dangerous degree of offshore wind farms, and to adopt comprehensive safety measures to control, or even to reduce the risk degree of offshore wind farm navigation to the minimum, and to achieve the best safety status. Regarding the risk assessment of navigation safety, currently the more commonly used methods include analytic hierarchy process (Dey, 2003), data envelopment analysis (Zhuang, 2005), and artificial neural network evaluation method (Mao, 2011), grey comprehensive evaluation method (Wen, 2003), fuzzy comprehensive evaluation method, etc. Based on the research focus of this paper and the author's knowledge level, this chapter only uses the fuzzy comprehensive evaluation method to evaluate and analyze the navigation safety of the Putian Port offshore wind farm, and does not use the hierarchical multi-level fuzzy comprehensive evaluation.

4.1 Overview of the fuzzy comprehensive method

The fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics. Comprehensive evaluation is a general evaluation of things or phenomena that are affected by multiple factors. Fuzzy mathematics is the use of mathematical methods to study and deal with objectively existing fuzzy phenomena. Fuzzy comprehensive evaluation is to make a general evaluation of the things or phenomena affected by a variety of factors with the help of fuzzy mathematics (William, 1996).

4.1.1 Basic principles

The fuzzy comprehensive evaluation is a comprehensive evaluation of something using fuzzy mathematics tools. The evaluation objective is regarded as a fuzzy set composed of multiple factors (called factor set "U"), and then the fuzzy set that these factors can constitute the evaluation level is called the evaluation set "V". V is the evaluation level of "U", which can be generally divided into five levels: excellent, good, medium, weak, and poor. Then calculate the attribution degree of each factor to the level according to the previous level division (determine the fuzzy matrix R), and then assign the weight "W" of each factor to the target. Through the fuzzy matrix synthesis operation, and the normalization process, a fuzzy comprehensive evaluation result set that can constitute the comprehensive evaluation model is obtained.

4.1.2 Calculation steps

(a) Determine the factor set "U" for the evaluation object

n evaluation indicators, $\mathrm{U} = (U_1, U_2, U_3, \ldots \ldots U_n)$

(b) Determine the evaluation set "V"

$\mathrm{V} = (V_1, V_2, V_3, \ldots \ldots V_n)$ Each level can correspond to a fuzzy subset;

(c) Establish the fuzzy matrix of attribution degree "R"

According to structure of the factor set, the factors that need to be evaluated are quantified one by one, and the attribution degree of the factor to the fuzzy subset is determined and the fuzzy matrix R is determined:

$$\mathrm{R} = \begin{bmatrix} \\ r_{11}\ r_{12} \cdots r_{1n} \\ r_{21}\ r_{22} \cdots r_{2n} \\ r_{31}\ r_{32} \cdots r_{3n} \\ \cdots\ \cdots\ \cdots\ \cdots \\ r_{n1}\ r_{n2} \cdots r_{nn} \end{bmatrix}$$

The element r_{ij} in the i-th row and j-th column of the matrix R represents the degree of attribution of the evaluated index to the fuzzy set of the V_j level from the factor U_i. The performance of an evaluated thing in terms of a certain factor U_i can be reflected by the fuzzy matrix R. From this point of view, fuzzy comprehensive evaluation requires more information.

(d) Determine the weight vector "W"

Traditionally, fuzzy comprehensive evaluation generally uses analytic hierarchy process to determine the weight vector of each factor involved. $\mathrm{W} = (W_1, W_2, W_3, \dots \dots W_n)$. The analytic hierarchy process is used to determine the relative importance between factors, thereby determining the weight coefficients, and normalization is required before synthesis (Gao, 2010).

(e) Calculate fuzzy comprehensive evaluation result "B"

Use a suitable operator to synthesize "W" with the "R" of each thing, and you will get the evaluation result vector B of each evaluated things. In practice, the most commonly used method is the principle of maximum degree of attribution, but the disadvantage of this method is that it will be unsuitable to use in some cases, losing a lot of information, and even get unreasonable evaluation results.

$$\mathrm{B} = \mathrm{W} \odot \mathrm{R} = (W_1, W_2, W_3, \dots \dots W_n) \odot \begin{bmatrix} r_{11}\ r_{12} \dots r_{1n} \\ r_{21}\ r_{22} \dots r_{2n} \\ r_{31}\ r_{32} \dots r_{3n} \\ \dots\ \ \dots\ \ \dots\ \ \dots \\ r_{n1}\ r_{n2} \dots r_{nn} \end{bmatrix} = (b_1, b_2, b_3, \dots \dots b_n)$$

Among them, the result b_i represents the attribution degree of the evaluated thing to the fuzzy set of V_i level on the whole (Shi, 2009).

4.2 The factor set and evaluation set of navigation safety of Putian Port offshore wind farm

According to the content of Chapter 3 of this paper, the fuzzy comprehensive evaluation factor set of risk assessment system of navigation safety of Putian Port offshore wind farm includes 5 fields: U_1 wind, U_2 ocean current, U_3 wave, U_4 recommended route, U_5 ship traffic flow.

According to the application of fuzzy comprehensive evaluation and the application results in the field of navigation at home and abroad, the evaluation factors of navigation safety of Putian Port offshore wind farm are divided into five levels: V = (nearly no risk, low risk, general risk, high risk, extremely high risk), the evaluation set can be expressed as: $\mathrm{V} = (V_1, V_2, V_3, V_4, V_5)$.

4.3 Establish the fuzzy matrix

4.3.1 Evaluation criteria for risk factors

At present, there is no unified standard for the degree of risk factors for the navigation safety in offshore wind farms. Therefore, in accordance with the usual practice of navigation safety in the field of shipping, the opinions of experts, and the research conclusions of scholars, the author made a quantitative and qualitative comprehensive analysis to determine the risk evaluation criteria of the risk factors affecting the navigation safety of the Putian Port offshore wind farm, which is a further construction prepare for fuzzy matrix. The evaluation criteria of risk factors are detailed in Table 4.

Table 4: The evaluation criteria of risk factors

Risk factors	Nearly no risk	Low risk	General risk	High risk	Extremely high risk
Wind (Maximum wind speed in Beaufort scale)	<3	3-4	5-6	7-8	>8
Ocean current (maximum velocity in meters/second)	<0.5	0.5-1.5	1.5-2.5	2.5-4.0	>4.0
Wave (maximum wave height in meters)	<0.1	0.1-1.25	1.25-4.0	4.0-6.0	>6.0
Distance between recommended route and wind farm (nautical miles)	>2.5	1.5-2.5	1.0-1.5	0.5-1.0	<0.5
Ship traffic flow (times/day)	<20	20-50	50-80	80-100	>100
Source：Author					

4.3.2 Obtained a fuzzy matrix of Putian Port offshore wind farm

Based on the observation data of AIS and meteorological station and the evaluation criteria constructed by 4.3.1 of this paper, taking offshore wind farm Area B as an example, the fuzzy matrix is obtained as follows:

$$R = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \end{bmatrix} = \begin{bmatrix} 0.05 & 0.17 & 0.35 & 0.31 & 0.12 \\ 0.02 & 0.30 & 0.37 & 0.19 & 0.12 \\ 0.07 & 0.18 & 0.41 & 0.25 & 0.09 \\ 0 & 0 & 0 & 1 & 0 \\ 0.10 & 0.36 & 0.45 & 0.09 & 0 \end{bmatrix}$$

4.4 Determine the factor weight

During the field study, using a scale of 1-9, the "weighting questionnaire" was distributed to the experts to score the importance of each factor set. Then, sort out the questionnaire, and calculate the weight and do a consistency test. After the test is passed, the normalized vector is the weight vector.

$$W = (0.083, 0.007, 0.092, 0.503, 0.315)$$

4.5 Fuzzy comprehensive evaluation vector of navigation safety

According to the fuzzy matrix established in 4.3.2 and the risk factor weights determined in 4.4, the fuzzy comprehensive evaluation vector of navigation safety in Zone B of Putian Port offshore wind farm can be calculated.

$$B = W \odot R = (0.083, 0.007, 0.092, 0.503, 0.315) \odot \begin{bmatrix} 0.05 & 0.17 & 0.35 & 0.31 & 0.12 \\ 0.02 & 0.30 & 0.37 & 0.19 & 0.12 \\ 0.07 & 0.18 & 0.41 & 0.25 & 0.09 \\ 0 & 0 & 0 & 1 & 0 \\ 0.10 & 0.36 & 0.45 & 0.09 & 0 \end{bmatrix}$$

$$= (0.068, 0.216, 0.309, 0.345, 0.062)$$

According to the fuzzy comprehensive vector result B, and the principle of maximum degree of attribution, the offshore wind farm can be considered to have a high risk level. Therefore, in the entire project construction and later operation and management process, it is necessary to strengthen risk management and formulate management measures and emergency plans to reduce the risk of navigation.

Chapter 5 Analysis of navigation safety of Putian Port offshore wind farm based on collision probability model

5.1 Calculation model of collision probability between ship and wind farm

In order to quantitatively analyze the safe distance between wind farms and shipping routes, Putian MSA and Wuhan University of Technology jointly proposed the wind farm collision probability calculation model in 2019 that based on factors such as wind, currents and ship traffic flow in the area near offshore wind farms, and wind farm scale. Then the safe distance between the offshore wind farm and the route is defined according to the standard of acceptable collision probability, so as to establish a safe distance calculation method that satisfies the collision probability of the ship and the wind farm within the acceptable level. Provide theoretical support for site selection and research on navigation risks of offshore wind farms (PTMSA et al, 2019).

5.1.1 Analysis of collision process between ship and wind farm

According to whether the ship's main engine fails, the collision between the ship and the wind farm can be divided into two types: drift collision and dynamic collision. Drift collision means that when the ship is sailing near the wind farm, the main engine failure causes the ship to lose control, and it may drift into the wind farm and collide with the wind turbine due to environmental factors such as wind and current. After the ship k loses control, it is dragged by wind and current, and its drift direction towards the wind farm. After a period of drift, it will enter the wind farm, as shown in Figure 4. If a ship k can save itself or get outside assistance in time before entering the wind farm, collisions can also be avoided. Dynamic collision refers to navigation errors caused by factors such as human error, bad weather and wind turbine interference. Ships fail to adjust their course in time when they are constantly approaching the wind farm, and the ships fail to avoid collisions, resulting in collisions with the wind farm. When navigating on a given route, the change of ship's heading is usually small. Therefore, a prerequisite for a dynamic collision is that the ship is sailing in the area where it will collide with the wind farm. Figure 4 shows the collision area where a ship J and the wind farm have a dynamic collision (PTMSA et al, 2019).

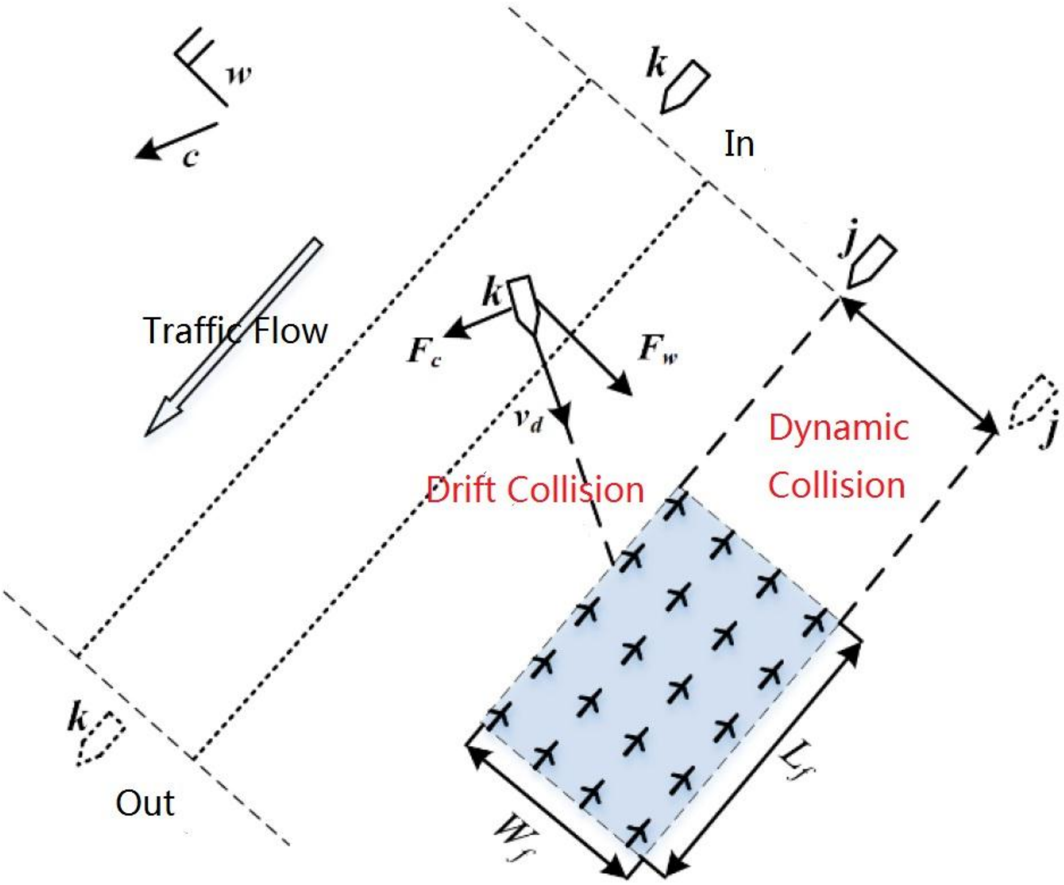

Figure 4 : Collision process between ship and wind farm

Source : PTMSA et al, 2019. Guidelines for the safety supervision of the construction of offshore wind farms

The collision probability model of ship and offshore wind farm takes the risk failure chain as the research theoretical basis, and expresses the probability of failure of each key factor in the collision accident between the ship and the wind turbine, or the possibility of the collision of the ship, so as to obtain the collision probability of the ship and the wind turbine. The method of calculating the collision probability of ships in the waters of offshore wind farms based on this model can be divided into the following steps:

Step 1: Collect historical AIS data of ships in the area where the wind farm is located within a certain period of time, perform data selecting and translation processing. At the same time, determine the scale data of wind farms and collect wind and current data near the wind farms.

Step 2: Obtain the type, speed, heading and position distribution of ships on the route near the wind farm through statistics of ship AIS data.

Step 3: Take the ship type, speed, heading, position distribution parameters, ship deadweight data, wind farm scale data, and wind and current distribution parameters as the basic parameters, and conduct multiple sets of simulation tests through designing test plans to verify the probability of collision model.

Step 4: Determine the collision probability threshold. When the calculated collision probability of the ship and the wind farm is lower than this threshold, the wind farm is considered to have little impact on the navigation safety of the ship. Based on the collision probability threshold, the impact of wind farms on the navigation safety of ships is analyzed.

5.1.2 Establish the calculation model

Based on the analysis of the collision process, the collision probability calculation model for ships and wind farms can be divided into drift collision and dynamic collision probability sub-models. By splitting the different stages of the collision process, in the drift collision probability sub-model, it is necessary to determine whether the ship has a fault, whether the drifting track is facing the wind farm, and whether rescue can be obtained before entering the wind farm. In the dynamic collision probability sub-model, judging whether the ship is located in the collision area mainly depends on the position of the ship and the course of the ship. Ships entering the collision area do not necessarily collide with the wind farm. Therefore, it is also necessary to consider whether the crew can take collision avoidance measures in time. On the basis of the above analysis, considering the influence of ship traffic volume and ship type, the calculation model of collision probability between ship and offshore wind farm is constructed as follow (PTMSA et al, 2019).

$$\mathrm{P} = P_1 + P_2$$

$$P_1 = \sum_i N_i \times P_{ib} \times \int_x^{x+B_i} f(x)\, dx \times P_{cw} \times P_{M1} \times P_{M2}$$

$$P_2 = \sum_i N_i \times (1 - P_{ib}) \times \int_0^{W_f} \int_{\theta_1}^{\theta_2} f(\theta) f(x)\, d\theta\, dx \times P_c \times P_r$$

The meaning of each parameter in the formula is shown in Table 5.

Table 5: The meaning of each parameter	
Parameter	Meaning
P	Average annual probability of collision between ship and wind farm
P_1	Average annual probability of a drift collision with a wind farm after a ship is out of control
P_2	Average annual probability of dynamic collision between ship and wind farm
N_i	Total traffic volume of Category i ships sailing on the sea route each year
P_{ib}	Probability of Category i ship out of control on the route
x	The width direction coordinates of the ship on the route
B_i	Average width of ships of category i
$f(x)$	Probability density function of ship's lateral distribution
P_{cw}	Probability of ship drifting to wind farm under wind and current
P_{M1}	Probability that the ship failed to avoid collision before it collided
P_{M2}	Probability that the ship could not receive effective external assistance before the collision
W_f	Wind farm boundary width
$f(\theta)$	Ship heading distribution density function
θ_1、θ_2	Critical value when the ship is in the collision area when the heading points to the boundary of the wind farm，$\theta1<\theta2$
P_c	Probability of failure of ship to take collision avoidance measures
P_r	Probability that the crew cannot make a collision avoidance response in time
Source：PTMSA et al，2019. Guidelines for the safety supervision of the construction of offshore wind farms	

5.1.3 Monte Carlo simulation

The Monte Carlo simulation method is a method that uses random numbers to solve calculation problems. It can obtain approximate solutions to problems through multiple sampling tests, and is widely used in the field of navigation safety (Yang et al, 2016). Calculate the collision probability between the ship and the wind farm by continuously generating random numbers that obey the distribution of ship characteristics and environmental characteristics (Zhou et al, 2015).

Ship position and ship heading generally follow a specific distribution, which can be obtained through field research. Environmental factors such as wind and flow conditions also follow certain rules, which can be obtained from the weather website. After obtaining the distribution functions of ship characteristics and environmental characteristics, the ship position, heading, main engine state and other characteristics as well as random numbers of wind and flow conditions are generated respectively. Based on this, combined with other relevant parameters, the collision probability between the ship and the wind farm can be obtained (Nie et al, 2019).

5.2 Analysis of collision probability between ship and Putian Port offshore wind farm

In the calculation model, some parameters such as N_i can be obtained through the big data of ship traffic flow obtained by AIS and an approximate solution can be obtained through using the Monte Carlo simulation method, and it is relatively constant. FUJII et al. (Fujii et al, 1998) used historical data to extract the frequency at which ship drift was corrected before the accident, so as to determine the value of some parameters such as P_c parameter. The P_r parameter can be used for reference from the empirical formula in the MARIN collision model (Mujeeb-ahmed et al, 2018), and it is considered that $P_r = \exp(-0.575 \times ds)$. Parameters such as W_f are related to the actual location of the offshore wind farm. Parameters such as P_{ib} are dually related to the actual location of offshore wind farms and statistical data.

This paper takes the planned offshore wind farm Area B in Putian Port as the research object, and the values of some parameters in the experiment are shown in Table 6.

<table>
<tr><td colspan="7">Table 6: Values of some parameters in the planned offshore wind farm Area B of Putian Port</td></tr>
<tr><td rowspan="2">Factor</td><td rowspan="2">Route length/n mile</td><td colspan="2">Ship traffic volume/ships</td><td rowspan="2">Angle between route and horizontal line/(°)</td><td rowspan="2">Ship loading situation</td><td rowspan="2">Ship lateral distribution</td></tr>
<tr><td>North direction</td><td>South direction</td></tr>
<tr><td>Value</td><td>10</td><td>334</td><td>431</td><td>52</td><td>full</td><td>N(0,770)</td></tr>
<tr><td rowspan="2">Factor</td><td rowspan="2">Heading distribution</td><td colspan="2" rowspan="2">Wind farm scale/m2</td><td colspan="2">Current</td><td rowspan="2">P_c</td></tr>
<tr><td>Average velocity/(m/s)</td><td>Main flow direction</td></tr>
<tr><td>Value</td><td>N(0,15)</td><td colspan="2">7 000×6 000</td><td>0.5</td><td>WSW</td><td>3×10^{-4}</td></tr>
<tr><td colspan="7">Source： Author</td></tr>
</table>

After the relevant parameter data are brought into the collision model, the average collision probability value of the distance between the wind farm and the nearby small and medium-sized ship's customary route under different conditions is obtained. The collision probability will vary slightly with the ship's speed, as shown in the Figure5.

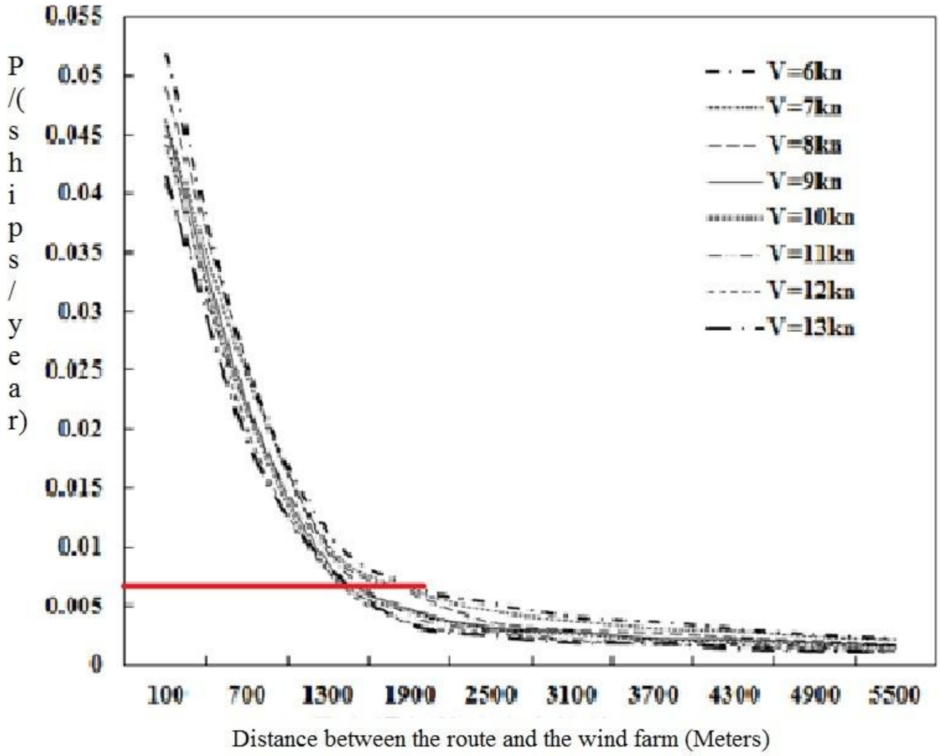

Figure 5: The calculate result of collision probability of a ship and a wind farm
Source: Author

According to the calculation results, it can be known that the collision probability of a ship and a wind farm is closely related to the distance between the route and the wind farm. In order to ensure the safety of ships sailing in the area of the offshore wind farm, the distance between the route and the wind farm can be controlled to reduce the probability of collision between the ship and the wind farm.

Based on the German acceptable risk standard in the study of collision risks of offshore facilities (Biehl et al, 2006), this paper sets the acceptable probability of collision accidents between ships and offshore wind farms in the route at 0.0067 times per year. On this basis, the distance between the wind farm and the passage is calculated when the average annual collision probability is less than 0.0067, and it is taken as a safe distance. Through calculation, it can be concluded that when the average ship speed is between 6 and 13 kn, the safe distance between the offshore wind farm Area B and the nearby small and medium-sized ships' customary route is 1,100 to 1,700 meters. Compared with the safe distance range proposed by the British MCA (MCA, 2016), the safe distance threshold obtained in this paper is smaller. Under the condition that the safety level of ship navigation meets industry standards, the proposed safe distance model can better optimize the allocation of marine resources, and at the same time, can reduce the compression of the original ship traffic flow and the change of the navigation environment. To a certain extent, it will reduce the impact of the construction of offshore wind farms on the navigation safety of ships.

Chapter 6 Conclusion and Suggestions

6.1 Conclusion

6.1.1 Summary of Chapter 2

Through the analysis of the navigation environment information of the Putian Port offshore wind farm, it can be found that there are many projects in the Putian Port offshore wind farm, which mainly concentrate in the waters near the Xinghua Bay. This water area is affected by the narrow tube effect of the Taiwan Strait. The wind force is relatively high throughout the year, and sometimes tropical cyclone and other extreme weather occur. This water area is regular half-diurnal tide, with large tidal range and high waves. There are various planned waterways and 7 customary routes near the Putian Port offshore wind farm. The daily flow of ships on each route is 18 to 135 vessels, and some customary routes overlap with the boundary of the offshore wind farm. On the whole, the navigation environment of the Putian Port offshore wind farm needs to be improved.

6.1.2 Summary of Chapter 3

Through the general analysis of the navigation safety risks of the Putian Port offshore wind farm, it can be found that the navigation safety risks of the Putian Port offshore wind farm can be classified into six aspects: natural environment, port environment, traffic environment, illegal transport activity, construction conditions, and management level, and can be further subdivided into more than 20 risk factors. But based on the research direction of this paper, the author only conducts further analysis on five factors including wind, ocean current, wave, recommended route, and ship traffic flow.

6.1.3 Summary of Chapter 4

Through analysis to the navigation safety of the Putian Port offshore wind farm by the fuzzy comprehensive method, it can be found that: Experts generally believe that two safety factors such as recommended route and ship traffic flow have a greater impact on the navigation safety of offshore wind farms, and the fuzzy comprehensive research of offshore wind farm Area B shows that the risk level in this area is high, and further risk management measures need to be taken.

6.1.4 Summary of Chapter 5

By using the collision probability model to analyze the navigation safety of the Putian Port offshore wind farm, it can be found that: Based on the ship collision probability model of the offshore wind farm jointly proposed by the Putian MSA and Wuhan University of Technology in 2019, through the statistical information such as AIS and meteorology, as well as the empirical formula proposed by other experts and scholars, the ship collision probability model is used to calculate the relationship between the probability of ship collision and the safe distance of offshore wind farms. The calculation results of Area B of the offshore wind farm show that the distance between the offshore wind farm and the navigation channel is acceptable, which is greater than the safe distance range of 1,100 to 1,700 meters calculated by the model.

6.1.5 Conclusion of the paper

Through the collected statistical data such as meteorology, hydrology, ship traffic flow, etc., it is possible to have a good understanding of the navigation safety environment of the offshore wind farms within the Putian Port. By identifying the safety factors, the navigation safety risks can be qualitatively analyzed, and the weight of the above safety factors can be further distributed by using the fuzzy comprehensive method, so as to further form a quantitative analysis of the navigation safety risk. However, the fuzzy comprehensive method can only calculate the probability distribution of each evaluation set, and cannot reveal the linear relationship between the evaluation result and a specific safety factor, and it is insufficient in quantitative analysis.

The collision probability model of offshore wind farms can be used to calculate the linear relationship between ship collision probability and the safe distance of offshore wind farms, which has a good guiding role in optimizing the safe distance of offshore wind farms. However, this model has high requirements on data accuracy and complex calculations, which can easily cause large deviations in results due to a small error. At the same time, the compatibility of this model is poor, and it is only suitable for the research on the collision probability of ships between a fixed area and a certain route. It has no effect on the study of navigation safety of offshore wind farms other than the collision factors.

The navigation safety research of offshore wind farms is a systematic project. It is necessary to use the fuzzy comprehensive method to conduct an overall quantitative analysis of each safety factors, and to use the collision probability model of the offshore wind farm to conduct a targeted quantitative analysis of the safety distance setting, and other suitable theoretical methods for specific research. The research on the Putian Port offshore wind farm, especially the offshore wind farm Area B, can show that although the risk level of this wind farm is high, the probability of ship collision is relatively small, and the safety situation is generally normal.

6.2 Suggestions for navigation safety management of Putian Port offshore wind farm

6.2.1 Making navigation safety assessment before construction

The construction enterprises shall, in accordance with the "Regulations of the People's Republic of China on the Administration of Navigation Safety of Water and Underwater Activities" and other laws and regulations concerned, entrust relevant qualified institutions to prepare a navigation safety assessment report as soon as possible, and apply to the maritime authority for conducting an audit. The navigation safety assessment report can be used as one of the documents submitted when applying for permits from maritime administrations. It can also be used as a reference document for the formulation of navigation safety maintenance plans and the implementation of navigation safety management during construction (Yang, 2019).

6.2.2 Designating a safe construction operation area during the construction period

In order to reduce the impact between the construction vessel and the nearby passing ships, when considering the water area of the construction activity, it is advisable to reserve room on the basis of the actual water area occupied. It is suggested that the construction activity water area of the wind farm should be expanded by 500~1,000m outside the peripheral wind turbine center as the construction activity water area during the construction period of the wind farm. The water area of the construction activity is a dynamic range, and the safe operation area can be adjusted in time with the adjustment of the construction plan during the actual construction process.

The setting of the safe operation area should take into account the requirements of construction operation and navigation safety as much as possible. On the premise of satisfying the construction operation, the safe operation area should be as far away as possible from the channel and anchorage waters. The construction vessel should strengthen the communication with the passing ships, and suspend construction when necessary to ensure the safety of navigation.

During the construction process, the construction unit should entrust an institution with relevant experience and expertise to formulate a safety protection plan during the construction period, and adopt corresponding safety measures to avoid accidents.

6.2.3 Setting up of aids to navigation and warning signs

In order to ensure the safety of the construction of the project and the navigation safety of nearby passing ships, it is recommended to set up relevant aids to navigation in the construction waters of the wind farm. The design of aids to navigation shall be arranged in conjunction with the channel planning, and shall be subject to the specific design and implementation of professional organizations. In severe weather such as strong wind and heavy fog, strong light (fog-through) signs and warning lights must be hung on the piles caps that have been built, especially on the peripheral water facilities, and a radar transponder should be added if necessary.

During the operation of offshore wind farms, appropriate aids to navigation for offshore wind farms should also be set up in accordance with relevant regulations and requirements by means of maritime navigation aids (including AIS virtual navigation aids), radar transponders, acoustic signals, luminous bands, and other equipment and methods.

6.2.4 Setting up of anti-collision facilities for wind farms during the operation period

Generally speaking, in order to slow down the collision of the operation and maintenance ship against the wind turbine when berthing, it is generally necessary to install a corresponding anti-collision pad at the berthing position, so as to buffer the ship berthing and ensure that the berthing part of the wind turbine can withstand the normal berthing of the ship. The anti-collision facilities for preventing large ships from colliding with the wind turbine can adopt separate anti-collision piles, steel box structure or other appropriate forms. The anti-collision facility should be specially designed. In addition, warning lights and warning signs should be arranged on the anti-collision facilities in accordance with relevant requirements (Yang, 2020).

6.2.5 Update of nautical chart

The following content should be marked on the nautical chart: (a) Special waters for wind farms, mark the special waters for wind farms with black dotted lines along the edge of the wind farm; (b) The exclusive water area of each wind turbine is marked with a dotted line at the range of 50 meters; (c) Submarine cables and their buried depths, and the scope of the cable protection area.

6.2.6 Real-time monitoring of offshore wind farms

The wind farm owner shall install CCTV, electronic fence and other on-site monitoring equipment in the wind farm as required. Maritime authorities mainly monitor offshore wind farms through VTS radar equipment. If necessary, offshore wind farm monitoring can also be used with maritime patrol boats for on-site cruises.

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Appendix

Questionnaire

<table>
<tr><td colspan="4">Personal information：</td></tr>
<tr><td>Name</td><td></td><td>Telephone</td><td></td></tr>
<tr><td>Profession and organization</td><td colspan="3"></td></tr>
<tr><td colspan="4">Questions：</td></tr>
<tr><td colspan="4">Q1： What are the risk factors affecting navigation safety of Putian Port offshore wind farm?</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Q2：How important are the above risk factors to navigation safety of Putian Port offshore wind farm？</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Q3： If you only consider the impacts on navigation safety of Putian Port offshore wind farm from the following five aspects, their importance degree is(Using a scale of 1-9，and 1 for least important， 9 for most important)？</td></tr>
<tr><td colspan="2">Wind</td><td colspan="2"></td></tr>
<tr><td colspan="2">Ocean current</td><td colspan="2"></td></tr>
<tr><td colspan="2">Wave</td><td colspan="2"></td></tr>
<tr><td>Recommended route</td><td>Distance between recommended route and wind farm</td><td colspan="2"></td></tr>
<tr><td>Ship traffic flow</td><td>The traffic density and ship length</td><td colspan="2"></td></tr>
<tr><td colspan="4">Q4:Suggestions on improving navigation safety of Putian Port offshore wind farm</td></tr>
<tr><td colspan="4"></td></tr>
</table>